Search for Lepton Flavor Violation in K^+ Decays

R. Appel[6,3], G. S. Atoyan[4], B. Bassalleck[2], D. R. Bergman[6*], N. Cheung[3], S. Dhawan[6], H. Do[6], J. Egger[5], S. Eilerts[2†], H. Fischer[2‡], W. Herold[5], V. V. Issakov[4], H. Kaspar[5], D. E. Kraus[3], D. M. Lazarus[1], P. Lichard[3], J. Lowe[2], J. Lozano[6§], H. Ma[1], W. Majid[6‖], W. Menzel[7¶], S. Pislak[8,6], A. A. Poblaguev[4], P. Rehak[1], A. Sher[3]
J. A. Thompson[3], P. Truöl[8,6], and M. E. Zeller[6]
[1] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[2] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA*
[3] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA*
[4] *Institute for Nuclear Research of Russian Academy of Sciences, Moscow 117 312, Russia*
[5] *Paul Scherrer Institut, CH-5232 Villigen, Switzerland*
[6] *Physics Department, Yale University, New Haven, CT 06511, USA*
[7] *Physikalisches Institut, Universität Basel, CH-4046 Basel, Switzerland*
[8] *Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland*
(February 7, 2008)

A search for lepton flavor violating decays, $K^+ \to \mu^+\mu^+\pi^-$, $K^+ \to e^+e^+\pi^-$, $K^+ \to \pi^+e^+\mu^-$, $K^+ \to \mu^+e^+\pi^-$ and $\pi^0 \to e^+\mu^-$, was performed using the data collected in E865 at the Brookhaven Alternating Gradient Synchrotron. No signal was found in any of the decay modes. At the 90% confidence level, the branching ratios are less than 3.0×10^{-9}, 6.4×10^{-10}, 5.2×10^{-10}, 5.0×10^{-10} and 3.4×10^{-9} respectively.

13.20.Eb,11.30.Hv,14.60.St

The apparent lepton flavor conservation observed so far in particle physics is conveniently accommodated in the Standard Model if the neutrino masses are zero. Such symmetry can be broken by new physics at a higher energy scale, such as Technicolor or Supersymmetry, or by neutrinos having Majorana masses. Extensive experimental efforts have been devoted to searches for lepton flavor violating kaon decays, $K_L^0 \to \mu^\pm e^\mp$ [1] and $K^+ \to \pi^+\mu^+e^-$ [2]. In this letter, we report the results of a search for $K^+ \to \mu^+\mu^+\pi^-$ ($K_{\mu\mu\pi}$), $K^+ \to e^+e^+\pi^-$ ($K_{ee\pi}$), $K^+ \to \mu^+e^+\pi^-$ ($K_{\mu e\pi}$) and $K^+ \to \pi^+e^+\mu^-$ ($K_{\pi e\mu}$). Unlike $K^+ \to \pi^+\mu^+e^-$, which only violates lepton flavor conservation, these decays also violate generation number conservation. In addition, the first three decays violate total lepton number conservation. $K_{\mu\mu\pi}$ and $K_{ee\pi}$ can proceed by the same mechanism as neutrinoless double β-decays of nuclei if neutrinos have Majorana masses. Although the first generation is well explored in neutrinoless double β-decays, $K_{\mu\mu\pi}$ provides a unique channel to search for effects of Majorana neutrinos in the second generation [4].

The previous searches for $K_{ee\pi}$, $K_{\mu e\pi}$ and $K_{\pi e\mu}$ were performed at CERN 25 years ago [3]. At the 90% confidence level (C.L.), the branching ratios were found to be $Br(K^+ \to e^+e^+\pi^-) < 1 \times 10^{-8}$, $Br(K^+ \to \pi^+e^+\mu^-) < 7 \times 10^{-9}$ and $Br(K^+ \to \mu^+e^+\pi^-) < 7 \times 10^{-9}$. In a reanalysis of data of a 1968 bubble chamber experiment [5], the best limit on $K_{\mu\mu\pi}$ was determined to be $Br(K^+ \to \mu^+\mu^+\pi^-) < 1.5 \times 10^{-4}$ at the 90% C.L. [4].

Experiment E865 at the Brookhaven Alternating Gradient Synchrotron was primarily designed to search for $K^+ \to \pi^+\mu^+e^-$ [2]. Because of its excellent capability in kinematic reconstruction and particle identification of K^+ decays to three charged particles, it has been exploited to study other decays such as $K^+ \to \pi^+e^+e^-$ [6], $K^+ \to e^+\nu e^+e^-$ and $K^+ \to \mu^+\nu e^+e^-$. In 1997, two special data sets were collected to study $K^+ \to \pi^+\mu^+\mu^-(K_{\pi\mu\mu})$ and $K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4}). Over 400 $K_{\pi\mu\mu}$ events [7] and 400,000 K_{e4} events were observed. We use the former to search for $K_{\mu\mu\pi}$, and the latter for $K_{ee\pi}$, $K_{\pi e\mu}$ and $K_{\mu e\pi}$.

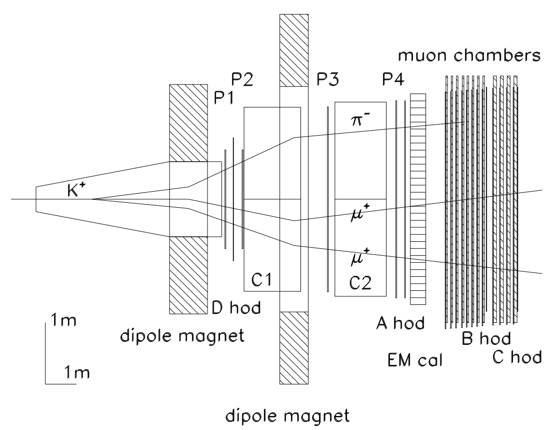

FIG. 1. Plan view of the E865 detector. A $K_{\mu\mu\pi}$ event is superimposed.

The detector (Fig. 1) and its performance has been described in other publications [2,6–8]. The apparatus resided in an unseparated 6 GeV beam directly downstream of a 5m long evacuated decay volume. The charged particles from K^+ decays were first separated in charge by a dipole magnet, then momentum analyzed in a spectrometer system consisting of proportional

chambers(P1-P4) and another dipole magnet. Particle identification was achieved by two sets of Čerenkov counters (C1) upstream and (C2) downstream of the spectrometer magnet, and a shashlyk-style electromagnetic calorimeter downstream of the spectrometer system, followed by a muon range stack consisting of steel plates interleaved with proportional tubes. For this study, the Čerenkov counters were filled with methane gas for high $e^{\pm}$ identification efficiency.

The trigger hodoscopes were located directly downstream of the first proportional chamber P1 (D-hod), upstream of the calorimeter (A-hod), and in the middle (B-hod) and at the end of the muon stack (C-hod). The first level trigger was constructed by requiring two charged particles on the right, and one charged particle on the left in the A and D hodoscopes and the corresponding calorimeter modules. In the next trigger level, particle identification information was applied.

The trigger designed for K_{e4} accepted events with e^+ but not accompanied by an e^-. Čerenkov light signals were required on the right side of both C1 and C2, and both Čerenkov counters on the left were required to have signal below one photo-electron, to suppress events with an e^- from the $\pi^0 \to e^+e^-\gamma$ decay (Dalitz).

The trigger designed for $K_{\pi\mu\mu}$ decay required one muon on each side of the detector. Each muon, for trigger purposes, was identified as a spatially correlated coincidence between the B and C hodoscope hits.

In the off-line reconstruction, events are required to have three charged tracks from a common decay vertex in the decay volume, a reconstructed kaon momentum consistent with the beam phase space distribution, and a timing spread between the tracks consistent with the resolution, typically about 0.5ns. Similar to the analysis of the $K_{\pi\mu\mu}$ events [7], a joint likelihood function is constructed based on the vertex quality, the kaon momentum vector, and the track χ^2. This is used to select events with high kinematic quality.

For $K_{\mu\mu\pi}$ events, muons are required to have momenta greater than 1.3 GeV/c, go through the muon stack and have corresponding hits in B-hod and C-hod. There should be sufficient muon chamber hits associated with the track, and energy deposition in the shower calorimeter should be consistent with minimum ionizing particles. The trigger requirement that there be one muon on the left and one on the right is not efficient for this decay because positively charged particles tend to populate the right side of the detector. The majority of the $K_{\mu\mu\pi}$ events which would be accepted by the trigger would have two μ^+'s on the right side of the spectrometer system, and one of the μ^+'s crossing to the left in the muon system downstream of the calorimeter (see Fig. 1). In a smaller fraction of events, one of the μ^+'s stays on the left side throughout the detector, and the other μ^+ and the pion on the right. Monte Carlo simulation shows that the trigger acceptance for $K_{\mu\mu\pi}$ is a factor of 2.7 smaller than that for $K_{\pi\mu\mu}$.

The background for $K_{\mu\mu\pi}$ comes from $K^+ \to \pi^+\pi^+\pi^-(K_\tau)$, with both π^+'s misidentified as μ^+'s. Although most of these background events have the reconstructed $\mu\mu\pi$ mass much lower than M_K because of the mass difference between muon and pion, events with pion decays in the spectrometer magnet can result in $\mu\mu\pi$ mass in the signal region. Because those events tend to have worse kinematic characteristics, a tight cut on the joint likelihood helps to reduce background.

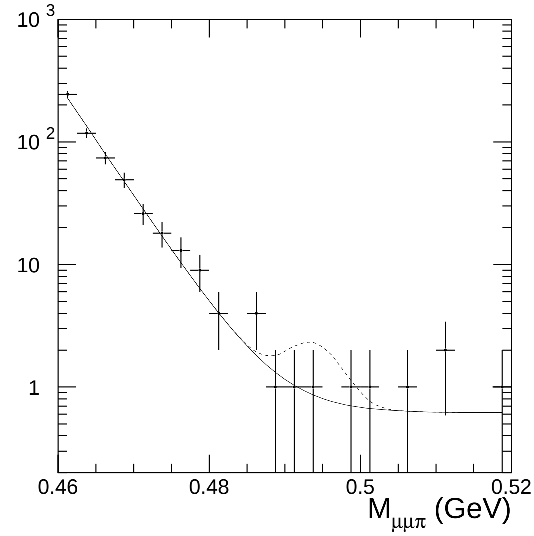

FIG. 2. The $\mu\mu\pi$ invariant mass distribution for $K_{\mu\mu\pi}$ candidates. The points with error bars are data, the solid line is a fit to an empirical function [7], and the dashed line is a fit that includes a signal at the 90% C.L. upper limit.

Figure 2 shows the reconstructed $\mu\mu\pi$ mass distribution after a cut on the joint likelihood function. The background within the signal region (0.4875 GeV $< M_{\mu\mu\pi} <$ 0.5025 GeV) is estimated by fitting the spectrum with an empirical function used in the $K_{\pi\mu\mu}$ analysis [7] with the signal region excluded. There are 5 events in the signal region where 5.3 background events are expected. Using the frequentist approach [9], the upper limit on the number of signal events is 4.8 at the 90% C.L.. Normalizing to K_τ, we obtain an upper limit on the $K_{\mu\mu\pi}$ branching ratio:

$$Br(K^+ \to \mu^+\mu^+\pi^-) < 3.0 \times 10^{-9}(90\%\text{C.L.}). \qquad (1)$$

For $K^+ \to e^+\pi^\pm\mu^\mp$ events, an e^+ is required on the right side with Čerenkov light associated with the track in both C1 and C2, and an E/p ratio of at least 0.8. The charged pion is required to have no significant signals in the Čerenkov counters associated with the track, and calorimeter responses consistent with minimum ionizing particles or hadronic showers. The $\mu^-(\mu^+)$ is required to be on the left(right), to reach the B-hod, and to have a

range in the muon stack consistent with its momentum. The minimum momentum for the muon is 0.75 GeV/c.

The main sources of background for $K^+ \to e^+\pi^\pm\mu^\mp$ decays are K_{e4}, when one of the charged pions is misidentified as muon, and K_τ, when one π^+ is mistaken for a muon and the other π^+ misidentified as e^+. The probability of misidentifying a π^+ as μ^+ is 5% due to pion decays and punchthrough. The probability of misidentifying a π^+ as an e^+ is 1.0×10^{-4}. This happens when the pion deposits most of its energy in the calorimeter, and at the same time there are photoelectrons associated with the track, either originating from scintillation or random activity. Since the threshold of the Čerenkov counters is 3.5 GeV for muons, the high energy muons in the beam halo can produce Čerenkov light. To reduce this misidentification probability, events with additional tracks on the right side, either electrons or high energy muons, are rejected from this sample.

In Fig. 3, data are compared to the Monte Carlo simulation of the background events from K_{e4} and K_τ, before a tight cut on the joint likelihood function is imposed. As can be seen, these two decay modes successfully account for the observed background.

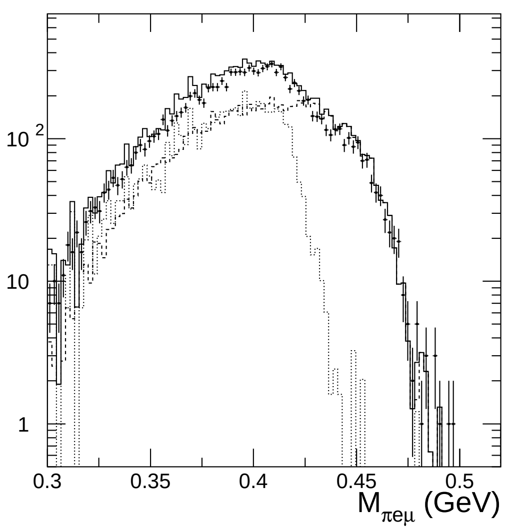

FIG. 3. $\pi e\mu$ invariant mass distribution for $K_{\pi e\mu}$ candidates before a tight cut on the joint likelihood function. The points are data, the dashed histogram is the K_{e4} Monte Carlo simulation, the dotted histogram is the K_τ Monte Carlo simulation, and the solid histogram is the sum.

Because of the undetected neutrino in K_{e4}, the K_{e4} background is greatly reduced by requiring the candidates to have a reconstructed kaon momentum vector within the beam phase space. Due to the large difference in rest masses, the K_τ background has a lower reconstructed invariant mass.

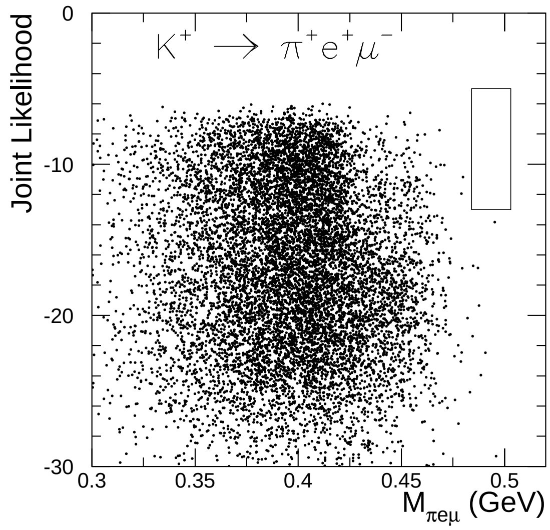

FIG. 4. Scatter plot of $M_{\pi e\mu}$ and joint likelihood function for $K_{\pi e\mu}$ candidate events. The box indicates the signal region.

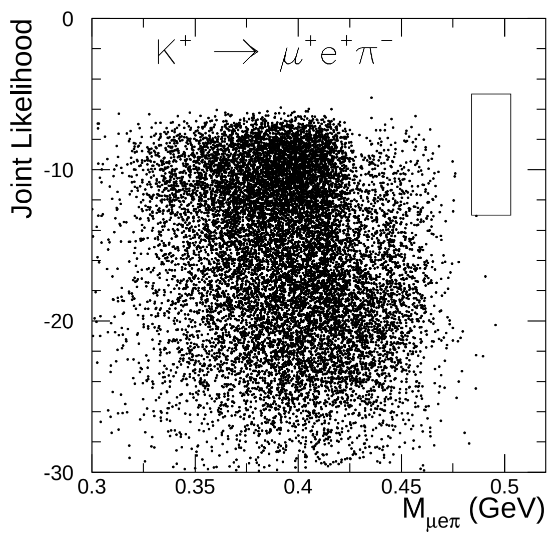

FIG. 5. Similar to Fig. 4, but for $K_{\mu e\pi}$.

Another potential background is $K^+ \to \pi^+\pi^0$, followed by π^0 Dalitz decay. Since the misidentification probability of e^- as μ^- is negligible, it does not contribute to $K_{\pi e\mu}$ background. For $K_{\mu e\pi}$ events, the reduction of the remaining Dalitz background to a negligible level is achieved by requiring $M_{ee} > 50$MeV, where M_{ee} is the invariant mass of e^+ and π^- with the π^- mass assigned to be the electron mass.

Figures 4 and 5 are the scatter plots of the invariant mass of the reconstructed candidate events vs. the joint likelihood function. The boxes indicate the signal region, which covers $\pm3\sigma$ in mass, and 80% acceptance in joint likelihood function. No signal events are observed.

The search for $K_{ee\pi}$ applies particle identification conditions as described above. The background comes from K_{e4} where the π^+ is misidentified as an e^+, and from K_τ where both π^+'s are misidentified as e^+'s. Because of the more significant mass difference between π's and e's these backgrounds are far away from the $K_{ee\pi}$ signal region. Figure 6 shows the scatter plot of M_{eep} vs. the joint likelihood function. Again, there are no events in the signal box. The background events in this plot are correctly accounted for by K_τ and K_{e4}.

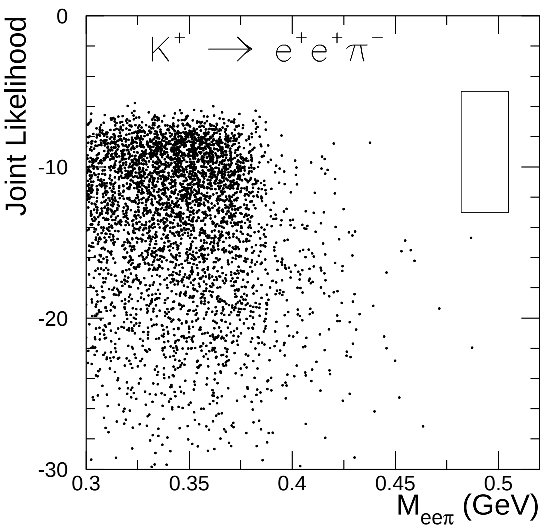

FIG. 6. Similar to Fig. 4, but for $K_{ee\pi}$.

The observation of no signal event for $K^+ \to \pi^+e^+\mu^-$ implies also a null result for the search of $\pi^0 \to e^+\mu^-(\pi_{e\mu})$, through the decay $K^+ \to \pi^+\pi^0(K_{\pi 2})$.

Table I lists the acceptances for the decays of interest. Normalized to K_{e4} decay, the null results of these searches are expressed in term of the 90% C.L. upper limit of the branching ratios,

Decay	Acceptance (%)
$\pi^+\pi^-e^+\nu$	3.93
$e^+e^+\pi^-$	1.54
$\pi^+e^+\mu^-$	1.90
$\mu^+e^+\pi^-$	1.97
$\pi^+\pi^0, \pi^0 \to e^+\mu^-$	1.38
$\pi^+\pi^+\pi^-$	6.25
$\mu^+\mu^+\pi^-$	0.71

TABLE I. The acceptances for K_{e4}, $K_{\mu e\pi}$, $K_{ee\pi}$, $K_{\pi e\mu}$, K_τ, $K_{\mu\mu\pi}$ and $K_{\pi 2}$+$\pi_{e\mu}$ decays, using Monte Carlo simulation. Detector efficiencies and effects of all kinematic and particle identification cuts are included.

$$Br_s < \frac{N_s \times Br_{Ke4} \times Acc_{Ke4}}{N_{Ke4} \times Acc_s}$$

$$Br(K^+ \to e^+e^+\pi^-) < 6.4 \times 10^{-10} \quad (2)$$

$$Br(K^+ \to \pi^+e^+\mu^-) < 5.2 \times 10^{-10} \quad (3)$$

$$Br(K^+ \to \mu^+e^+\pi^-) < 5.0 \times 10^{-10} \quad (4)$$

$$Br(\pi^0 \to e^+\mu^-) < 3.4 \times 10^{-9} \quad (5)$$

$Acc_{Ke4}(Acc_s)$ is the acceptance to K_{e4} (signal) decay, and $N_s = 2.44$, $Br_{Ke4} = 3.91 \times 10^{-5}$, $N_{Ke4} = 378,000$. For $\pi_{e\mu}$, the $K_{\pi 2}$ branching ratio of 0.21 is taken into account.

The limits on $K_{\pi e\mu}$, $K_{\mu e\pi}$ and $K_{ee\pi}$ represent an improvement of more than a factor of 10 over the previous searches [3]. The upper limit on Br($\pi^0 \to e^+\mu^-$) and our result of Br($\pi^0 \to \mu^+e^-$) $< 3.8 \times 10^{-10}$ [2] can be compared to the previous best limit of $[Br(\pi^0 \to \mu^+e^-) + Br(\pi^0 \to \mu^-e^+)] < 1.72 \times 10^{-8}$ [10]. The new upper limit on $K_{\mu\mu\pi}$(Eq. 1) is a factor of 50000 better than the previous experimental bound. The implications of this result are discussed in [11].

We thank L. Littenberg, R. Shrock and K. Zuber for useful discussions. We gratefully acknowledge the contributions to the success of this experiment by the staff and management of the AGS at the Brookhaven National Laboratory, and the technical staffs of the participating institutions. This work was supported in part by the U. S. Department of Energy, the National Science Foundations of the USA(REU program), Russia and Switzerland, and the Research Corporation.

* Present address: Rutgers University, Piscataway, NJ
† Present address: The Prediction Co. Santa Fe, NM
‡ Present address: Albert-Ludwigs-Universität, Germany
§ Present address: University of Connecticut, Storrs, CT
‖ Present address: LIGO/Caltech, Pasadena, CA
¶ Present address: Universitätspital, Zürich, Switzerland

[1] D. Ambrose *et al.*, Phys. Rev. Lett. **81**, 5734 (1998).
[2] R. Appel *et al.*, submitted to Phys. Rev. Lett. (hep-ex/0005016)
[3] A. M. Diamant-Berger *et al.*, Phys. Lett. **62**, 485 (1976)
[4] L. Littenberg and R. Shrock, Phys. Rev. Lett. **68**, 443 (1992)
[5] C. Chang *et al.*, Phys. Rev. Lett. **20**, 510 (1968)
[6] R. Appel *et al.*, Phys. Rev. Lett. **83**, 4482 (1999).
[7] H. Ma *et al.*, Phys. Rev. Lett. **84**, 2580 (2000).
[8] R. Appel *et al.,* to be submitted to Nucl. Instr. Meth.
[9] G. J. Feldman and R. D. Cousins, Phys. Rev. **D57**, 3873 (1998).
[10] P. Krolak *et al.*, Phys. Lett. **B320**, 407 (1994).
[11] L. Littenberg and R. Shrock, *Implications of Improved Upper Bounds on* $|\Delta L| = 2$ *Processes.* to be submitted to Phys. Lett. B. (hep-ph/0005285).